Statistical Properties of the Acoustic Field in Inhomogeneous Oceanic Environments – Team Overview

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Grant Numbers: N00014-01-F-0317, N00014-02-IP2-0039, and N00014-02-IP2-0019
http://www.etl.noaa.gov

LONG-TERM GOALS

- To develop an effective method of description of statistical properties of acoustical signals and calculation of false alarm rate for a given probability distribution of locations of acoustic source(s) in space.

- To quantify the degree to which uncertainty in the knowledge of cross-range variation of environmental parameters and their variation in time (or purely statistical information on the variations) degrades the ability to detect, locate, and track targets acoustically.

OBJECTIVES

1. To develop an effective numerical algorithm of calculation of second statistical moments of the acoustic signals measured by a set of receivers located on sea bottom or arbitrarily distributed in space for inhomogeneous ocean waveguide (including the case of uneven bottom) in terms of probability distributions of source location.

2. To investigate probability distributions of acoustical signals for typical environments including both deep water and littoral cases.

3. To develop an efficient formalism of transferring uncertainty in the 4-D spatial-temporal fields of environmental parameters into uncertainties of observable acoustic quantities.

4. To quantify the amount of environmental information necessary to achieve a specified accuracy of acoustic field modeling and to determine, for various nearshore hydrodynamic processes of interest, when 2-D (as opposed to 3-D and 4-D) environmental and propagation models are acceptable.

5. To develop a numerical algorithm for predicting statistical moments of acoustic signals in underwater waveguides with horizontally-inhomogeneous and time-dependent parameters.

APPROACH

Our approach to modeling acoustic effects of cross-range environmental gradients, oceanic currents, and time-dependence of the sound speed and the problem geometry, is based on considering these

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Statistical Properties of the Acoustic Field in Inhomogeneous Oceanic Environments- Team Overview**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **CIRES/Univ. of Colorado and NOAA/OAR,Environmental Technology Lab.,R/ET1, 325 Broadway,,Boulder,,CO, 80305**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

effects as perturbations with respect to sound propagation in a range-dependent, motionless, stationary waveguide. The problem is solved analytically for the three leading terms of the perturbation series. Account of the second-order terms is crucial because it is these terms that are responsible for ray travel time and mode phase biases. The perturbation solution is used to determine statistical properties of various acoustic observable quantities in terms of respective statistical properties of environmental parameters. The task of relating statistical properties of the sound field to statistical properties of the environment is greatly facilitated by the fact that the perturbation theory gives variations in travel times and other acoustic quantities as integrals in the source/receiver vertical plane of certain functions of cross-range gradients and time derivatives of environmental parameters. Kernels of the integrals are determined by the acoustic field in an unperturbed, stationary, range-dependent environment and are independent of the currents, the cross-range environmental gradients and the time derivatives.

To quantify uncertainties in the acoustic field and associated probabilities of the detection and false alarm rate we use the concept of a scattering matrix (SM) for acoustic modes. SM describes the process of transformation of modes when propagating through an inhomogeneous region. SM depends on the parameters of the inhomogeneities but does not depend on coordinates of the source and receivers. Thus the functional dependencies on the environmental parameters and positions of the source and receivers are multiplicative and can be studied separately. In particular, if the SM is exactly known and position of the source is unknown, uncertainties of the detection can be expressed in terms of convolution of SM with an assumed probability distribution of the source location. On the other hand, if SM is not exactly known, additional uncertainty in source detection can be expressed in terms of statistical moments of SM itself.

The key individuals currently involved in this work are Dr. Oleg A. Godin (CIRES/Univ. of Colorado and NOAA/ETL) and Drs. Alexander G. Voronovich and Valery U. Zavorotny (NOAA/ETL). Strength of our small team with only two PIs is a very close, daily collaboration of the investigators on most aspects of the research. A. Voronovich is primarily responsible for developing and implementing the scattering matrix formalism and an improved description of nonlinear internal gravity waves (IW). V. Zavorotny is involved in numerical simulations of the acoustic field and contributes his expertise on waves in random media. O. Godin takes the lead in the theory and modeling of the 3-D and 4-D effects in underwater sound propagation.

WORK COMPLETED

A quasi-stationary approximation has been developed to efficiently model acoustic effects of the time-dependence of the environmental parameters, such as sound speed and ocean surface variations due to internal and surface gravity waves, occurring on various time scales. In the quasi-stationary approximation, determining acoustic travel time, phase, and frequency is reduced to calculation of certain quadratures along the trajectory which would have been taken by the wave in the stationary medium. It has been shown that, unlike the commonly utilized frozen medium approximation, the quasi-stationary approximation allows one to accurately simulate effects of the ocean nonstationarity on acoustic travel times, nonreciprocity, and signal spectrum (Godin, 2002g, e, f).

New and improved techniques have been put forward to incorporate data on oceanic currents into acoustic propagation models based on a coupled-mode representation of the field (Godin, 2002b) and a wide-angle, energy-conserving, 3-D parabolic approximation (Godin, 2002d).

Using theoretical results of (Godin, 2002i), a numerical algorithm has been created to predict statistical moments of ray travel times in the ocean where 3-D random inhomogeneities are superimposed on a range-dependent deterministic background. The algorithm has been applied to simulate the effects of random horizontal refraction of sound caused by internal waves.

The SM concept has been applied to the problem of sound propagation through perturabations due to IW solitons in shallow water. SM was calculated in the Born approximation. Its spectrum and appropriate eigenvectors were also computed for different soliton amplitudes.

Hydrodynamic description of the IW solitons for a case of a two-layer fluid with constant Brunt-Vaisala frequencies separated by a density jump has been obtained (Voronovich, 2002). This model is not restricted to the case of relatively weak KdV solitons and allows consideration of the “strong” solitons with amplitudes comparable to the layers’ thickness.

Equations governing the first and second statistical moments of the acoustic field have been developed in the Markov approximation. A preliminary version of the diffusion approximation to those equations has been obtained, and the matrix of diffusion coefficients has been calculated. The results for RMS of horizontal refraction angle were compared with the experimental data (obtained in the framework of another ONR-sponsored project).

With funds from a conference support grant, N00014-02-IP2-0019, a visit by Drs. Arthur B. Baggeroer (Massachusetts Institute of Technology), James F. Lynch (Woods Hole Oceanographic Institution), and William A. Kuperman (Scripps Institution of Oceanography) to Moscow, Russia was organized. Drs. Baggeroer, Lynch, and Kuperman gave invited lectures at the IX Brekhovskikh’s Ocean Acoustics Conference. The US delegation, which also included Drs. Jeffrey A. Simmen (ONR), Alexander Voronovich (NOAA/ETL) and Oleg A. Godin (Univ. of Colorado and NOAA/ETL), helped to pay tribute to Leonid M. Brekhovskikh’s groundbreaking contributions to underwater acoustics and physical oceanography on occasion of his 85th birthday. The Brekhovskikh’s Ocean Acoustics Conference is a biannual meeting which covers a broad range of subjects associated with the underwater acoustics and the acoustical oceanography. Traditionally, it is the major event in this field for scientists in Russia and the Commonwealth of Independent States. Participation of leading acousticians from the US in the IX Brekhovskikh’s Ocean Acoustics Conference elevated it to a truly international level, allowed them to gather rather complete information about status of underwater acoustics and acoustical oceanography in Russia, and helped to forge closer, more productive ties between Western scientists and research groups currently active in the former USSR.

RESULTS

Deviation of wave trajectory from the source/receiver vertical plane leads to ray travel times and adiabatic normal mode phases being *less* than predicted by the uncoupled azimuth approximation which neglects cross-range environmental gradients. Internal waves appear to be the major source of the travel time bias in the deep ocean. Magnitude of the bias is proportional to path-averaged energy of the internal waves, increases as the range squared, and is maximal for rays with shallow upper turning points. It can exceed 10 ms at the range of 1Mm, assuming the internal waves have the Garrett-Munk spectrum. For continuous waves, the travel time bias due to horizontal refraction translates into a change in the conditions of interference of individual arrivals. At 1 Mm range, neglect of the

horizontal refraction due to the internal waves results in O(1) relative phase errors and, consequently, significant transmission loss errors at frequencies as low as 50 Hz.

In shallow water, horizontal refraction can lead to comparable effects at much smaller ranges when there are strong cross-range environmental gradients along the acoustic track, such as a bottom slope or variation of sound speed in the horizontal plane due to an oceanographic front or an IW soliton. Unlike the deep water case, significance of the horizontal refraction proves to be very sensitive to azimuthal direction from a source to a receiver. Sound propagation has been considered over 13.5 km track between a sound source and a vertical line array during the 1995 Shallow-Water Acoustics in Random Medium (SWARM) experiment (Apel *et al.*, 1997). Internal tide generated at the shelf brake was a major source of environmental variability at the SWARM site, with up to 10 m vertical displacements in 80 m-deep ocean. Neglecting ocean bottom slope, ray travel time corrections due to horizontal refraction have been found to exceed 11 ms for source and receiver at 20 m depth when the internal tide propagates exactly perpendicularly to the source/receiver vertical plane. A 3° uncertainty in the azimuthal direction of the soliton propagation translates into up to 10 ms change in the correction, which amounts to O(1) change in relative phase of different ray arrivals and consequent significant change in the CW transmission loss at sound frequencies above 80 Hz. Horizontal refraction is also responsible for unusually rapid variation of signal spectrum and travel times of individual arrivals. When an IW soliton propagates perpendicularly or almost perpendicularly to the acoustic track, travel times of individual arrivals and travel time differences of arrivals with different grazing angles can change by up to 10 ms during a few minutes. This is because the acoustic travel time and phase corrections due to horizontal refraction are proportional to path-averaged value of the square of the cross-range sound-speed gradient, and the gradient changes rapidly when a soliton with a sharp front propagates through the acoustic track.

An important advance has been made in development of a hydrodynamic model of IW solitons. Existing models usually consider weakly-nonlinear IW case where the solitons are described by KdV equation. However, such models are not applicable to the cases where soliton amplitude is comparable to or even greater than thickness of fluid layers. Such solitons are often observed in the littoral areas (Stanton and Ostrovsky, 1998). A “2.5-layer model” has been suggested for description of such strong solitons. In the new model, stratification is assumed to consist of two layers with constant buoyancy frequency separated by a density jump. The results of numerical simulation performed for the case of IW observed during COPE experiment (Stanton and Ostrovsky, 1998) have been compared with experimental data. The model and the data appear to be in a good agreement.

In simulating sound propagation in a range-independent shallow-water waveguide disturbed by an IW soliton, the scattering matrix was found to have only three significant eigenvalues. This means that there are only three particular configurations of the acoustic field (i.e., superposition of the acoustic modes with specific amplitudes determined by appropriate eigenvectors) that are significantly affected by the soliton. This information allows one to tune a detection algorithm in such a way that those configurations of the field will have the smallest impact.

In an effort to develop an efficient algorithm for calculating statistical moments of the acoustic field, basic governing equations were obtained in the Markov approximation. The expressions for the average scattering matrix and scattering cross-sections have been obtained. Those equations are not very well suited for immediate numerical implementation because of the dependence on cross-component *k* of the wave vector and the need to integrate over *k*. Further simplification of these

equations will be introduced using the narrowness of the scattering diagram, which will allow us to make the diffusion approximation with respect to horizontal angles.

IMPACT/APPLICATIONS

The most immediate impact of this work will be on the use of deterministic models of underwater sound propagation for making tactical decisions. Results of this work will quantify, in a statistical sense, reliability of predictions for various acoustic observables obtained assuming range-dependent ocean and disregarding horizontal refraction and effects due to ocean currents and time-dependence of the environmental parameters.

This work should also have an impact on design of detection algorithms. The algorithms should be made insensitive to the components of the acoustic field which are most affected by the unknown inhomogeneities of the ocean waveguide associated, e.g. with IW solitons or bottom profile features. Those field configurations are described by eigenvectors of scattering matrix. The results obtained will allow quantifying the effects of uncertainties in the description of oceanic environment on the probability of detection and the false alarm rate.

TRANSITIONS

None yet.

RELATED PROJECTS

Experimental Verification of a Horizontal-Refraction-Tomography Technique Using North Pacific Acoustic Laboratory Data (N00014-02-IP2-0035).

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